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## A PRELIMINARY TORNADO FORECASTING SYSTEM FOR KANSAS AND NEBRASKA

F. G. SHUMAN AND L. P. CARSTENSEN

Short Range Forecasting Development Section, U. S. Weather Bureau, Washington, D. C.

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### ABSTRACT

A study is made of the possibility of associating certain characteristics of the weather situation at 1500 GMT with the occurrence of tornadoes within a specified area during the succeeding 12 hours. The parameters selected were all determined objectively. The system devised was able to separate out a group which included about 30 percent of all reported tornadoes and for which tornadoes were reported in about 60 percent of the cases. The main significance of the study is that apparently the tornado forecasting problem can be successfully treated with the objective forecasting techniques developed in the last decade.

### INTRODUCTION

It has generally been realized that tornadoes should be forecast, because of their violent and destructive nature. On the other hand, they occur infrequently in time and widely scattered in space. In order that tornado forecasting may contribute to the saving of life and property, the forecasts should be reliable, otherwise the public would soon become insensitive to warnings.

A quantitative analysis of factors affecting tornado occurrence should contribute greatly to the reliability of forecasts issued. Quantitative analyses have the further advantage that they may be passed to novice forecasters in a form easily grasped and understood. There have been some recent important contributions to tornado forecasting, such as those by Lloyd [1], Showalter and Fulks [2], and Fawtush, Miller, and Starrett [3]. These studies, however, place their main emphasis on conditions contemporary to tornado occurrence. These conditions must be forecast, often in rapidly changing situations. The principles evolved in these studies, and other principles known for many years, do not generally permit of their quantitative application.

It must be recognized that not all tornadoes can be forecast with a high degree of reliability. Since one of the principal requirements of tornado forecasting is

reliability, the forecaster is faced with the necessity of issuing forecasts only on days when it is relatively certain that tornadoes will or will not occur. Thus, by some criteria, objective or otherwise, he must be able to separate in advance all days into three groups:

- A. Days on which it is certain tornadoes will not occur.
- B. Days on which it is certain they will occur.
- C. Days on which tornado occurrence is uncertain.

In order to facilitate the discussion, days falling under group A will be called "non-threat days." Similarly, days falling under group B and group C will be called "threat days" and "uncertain days," respectively. The relative value of the forecasts may be judged by the sizes of the three groups relative to each other, and by the degree of certainty in the first two.

Before beginning on a program of making tornado forecasts for the general public, the forecaster should have a good estimate of how reliable his forecasts will be. This requires either a carefully controlled program of practice forecasting and verification over a long period of time, or a quantitative study of factors affecting tornado occurrence in the past. It would be preferable to accomplish both of these tasks, if the pressure of the times permits.

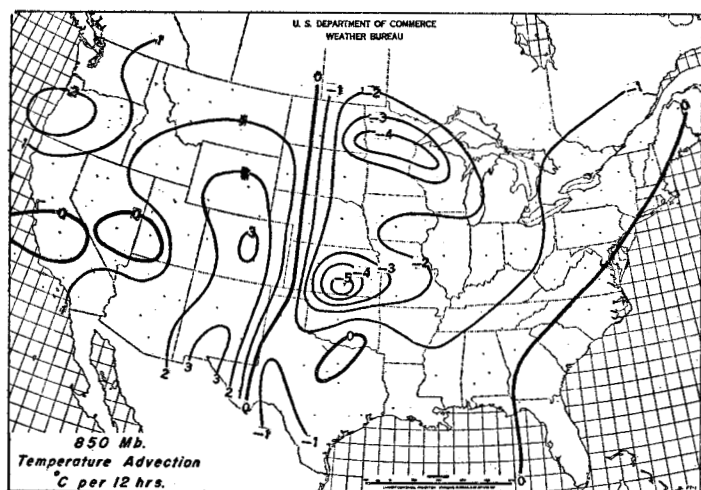


FIGURE 1.—Composite chart of 850-mb. temperature advection on 13 major tornado days during the 24 months of March through June, 1945 through 1950. Only days on which tornadoes occurred in the forecast area (roughly, Kansas and Nebraska—see fig. 4) are included in this composite chart.

The aim was adopted, early in this study, of finding out what is possible in the way of separating tornado days from non-tornado days by quantitative analysis of factors associated with tornado occurrence at lag. The result reported here is an objective system of forecasting tornadoes within a limited area and period. It should prove to be a valuable guide to the forecaster.

The synoptic picture resulting from this study is that tornadoes will occur within 12 hours in Kansas and Nebraska when

1. Maritime tropical air is over or southeast of the area,
2. A deep cold air mass lies west of the area,
3. A well defined pressure trough at 700 mb. lies above the area, and
4. The temperature trough and pressure trough at 700 mb. are out of phase so that there is a strong contrast in temperature advection across the trough.

These physical conditions are often fulfilled when there is a Low over or slightly to the west or north of the area. The relation of tornado occurrence to these conditions will not surprise a forecaster familiar with the meteorology of the two States. The contribution made by this study is the quantitative measure of these conditions represented in figures 2 and 3 which are explained below.

#### QUANTITATIVE ANALYSIS OF FACTORS ASSOCIATED WITH TORNADO OCCURRENCE

At the outset it should be pointed out that this forecast system represented by the analysis has not been tested on independent data. Independent data which might be used for testing this system would be compromised as test data for another system or for an improvement on this system. Due to scarcity of data, testing will be confined to current data until a forecast system has been

developed which is considered as final an answer as possible.

The source of data on tornado occurrence was files of the Climatological Division of the U. S. Weather Bureau. The data analyzed were from the 14 months of May and June 1946–50 and April 1947–50. The forecast system, therefore, should be used only during the months of April, May, and June, although the principles upon which it is based may apply to all seasons. The forecast period is from 0900 CST to 2100 CST. The forecast area is bounded by the meridians 95° and 102° W. and by the latitude circles 38° and 42° N. This area comprises roughly two-thirds of the combined territory of Kansas and Nebraska (see fig. 4).

For the purposes of this discussion the phrase, “non-tornado days”, will be taken to mean days on which tornadoes were not reported in the forecast area or period. “Tornado days” will mean days when at least one tornado was reported in the forecast area and period. A tornado day will be called “major” if at least 3 tornadoes occurred on that day, at least 2 of which were 100 or more miles apart. Other tornado days will be called “minor”.

Many variables were tried as indicators of the synoptic conditions listed in the Introduction. The final selection was made entirely on the basis of their ability to separate all days into the three categories listed on page 233. Four variables were chosen. They are:

- $X_1$ , the 0900 CST (1500 GMT) surface dew point (° C.) at either Columbia, Mo. or Dodge City, Kans., whichever is higher
- $X_2$ , the 0900 CST (1500 GMT) difference (° C.) between the 500-mb. temperature at Grand Junction and the surface temperature at either Columbia or Dodge City, whichever has the higher dew point
- $X_3$ , the 0900 CST (1500 GMT) 700-mb. temperature advection (° C. per 12 hrs.) over the triangle with vertexes at Dodge City, Oklahoma City, and Omaha
- $X_4$ , the 0900 CST (1500 GMT) 700-mb. temperature advection (° C. per 12 hrs.) over the triangle with vertexes at Albuquerque, Big Spring, and North Platte.

$X_3$  and  $X_4$  were computed by triangulation under the assumption that the wind is geostrophic and the 700-mb. height ( $z$ ) and temperature ( $T$ ) fields are linear within each triangle. The formulas used for computations are:

$$X_3 = .008841 \times \left\{ \begin{aligned} &z_{OMA}(T_{DDC} - T_{OKC}) \\ &+ z_{DDC}(T_{OKC} - T_{OMA}) \\ &+ z_{OKC}(T_{OMA} - T_{DDC}) \end{aligned} \right\}$$

$$X_4 = .003147 \times \left\{ \begin{aligned} &z_{ABQ}(T_{BGS} - T_{LBF}) \\ &+ z_{BGS}(T_{LBF} - T_{ABQ}) \\ &+ z_{LBF}(T_{ABQ} - T_{BGS}) \end{aligned} \right\}$$

The derivation of these formulas is carried out in an appendix to this paper. In these formulas,  $X_3$  and  $X_4$  are expressed in Celsius (centigrade) degrees per 12 hours,  $z$  in feet, and  $T$  in degrees Celsius (centigrade). Positive values of  $X_3$  and  $X_4$  indicate cold air advection, negative values warm air advection.

Figure 1 shows a clue which led to the use of temperature advection as variables. It is a chart of 850-mb. geostrophic temperature advection computed from mean height and temperature charts of major tornado days during March, April, May, and June, 1945-50, a total of 6 years. There were 13 such days during the 6 years. The 13 major tornado days represent only days in which tornadoes occurred in our forecast area, that is, roughly, Kansas and Nebraska.

Temperature advection data at 850, 700, and 500 mb. were compiled for the two triangles, and various combinations of these data were tried as predictors. Temperature advection data at 700 mb. for both triangles were finally selected because they separated best the tornado days from the non-tornado days. It will be noted that the triangles are designed to cover the maximum and minimum in figure 1. Inspection of the mean 700- and 500-mb. height and temperature charts for the same days which figure 1 represents revealed that the triangles also fit the regions of cold and warm temperature advection at these levels.

In figure 2,  $X_1$  and  $X_2$  were plotted against each other for each day of the 14 months of development data. Note that the upper right hand corner is ruled off. This was done in such a way that the ruled-off area contains practically all of the tornado days. Of 38 tornado days, only 2 are outside the ruled-off area.

Days which lie outside the ruled-off area are non-threat days, since the forecaster may be relatively certain that these days will be non-tornado days. Days which lie within the ruled-off area are threat days plus uncertain days, since figure 2 gives the forecaster only the information that these days are not non-threat days. There are 166 threat days and uncertain days, and 257 non-threat days in figure 2. Originally there were 425 days in the 14 months. Upper air data were lacking for 2 days, both of which were non-tornado days.

In figure 3,  $X_3$  and  $X_4$  were plotted against each other for only figure 2 tornado threat days. In figure 3 also, a line was drawn separating the cases into two groups. The line was so drawn that one group contained a substantial number of days, most of which were tornado days.

Days in this group, which lies in the upper left portion of figure 3, are threat days, since the forecaster may be relatively certain that these days will be tornado days. The days lying in the remainder of figure 3 are the uncertain days of this system, in the sense that they have not been satisfactorily separated. There are 20 threat days and 135 uncertain days in figure 3. One or more of the necessary upper air soundings were missing for 11 of the 166 threat days and uncertain days of figure 2. Of the 11

days, 2 are tornado days, 9 non-tornado days. Of the 34 tornado days plotted in figure 3, 12 are threat days, 22 are uncertain days.

As stated previously, the forecaster must be able to separate in advance all days into three groups.

- A. Non-threat days: days on which he is certain tornadoes will not occur. In this forecast system, this group corresponds to the non-threat days of figure 2.
- B. Threat days: days on which he is fairly certain tornadoes will occur. This group corresponds to the threat days of figure 3.
- C. Uncertain days: days on which he is uncertain whether or not tornadoes will occur. This group corresponds to the uncertain days of figure 3.

The relative value of any system, objective or otherwise, may be judged by the sizes of these three groups relative to each other, and the degree of certainty in the first two. The relative sizes and the degrees of certainty are listed below. It will be noted that data were available for only 412 days of the 425 days in the 14 months of development data. Thirty-six of the 412 days were tornado days, 376 non-tornado days. The climatological probability of a day becoming a tornado day is, therefore,  $P_{ct} = 36/412 = .087$ , as indicated by the 412 days for which data were available.

|              | Relative size | Forecast       | Degree of certainty |
|--------------|---------------|----------------|---------------------|
| Group A----- | 257/412=.623  | No tornadoes-- | 255/257=.992        |
| Group B----- | 20/412=.049   | Tornadoes----- | 12/20=.600          |
| Group C----- | 135/412=.328  | -----          | -----               |

One question which will inevitably be asked is, "In order to obtain a high degree of certainty in Group B, must the size of Group B be made so small that it no longer contains a substantial number of the tornadoes which occur?" The answer to this question as it applies to this study may be judged from the fact that, of the 36 tornado days for which data were available, 12 fall into Group B. This means that if the system holds in the future, it will forecast  $12/36 = 1/3$  of all the tornado days which occur.

The four variables used in this study were suggested by a set of composite charts of tornado days. The Short Range Forecasting Development Section has prepared for major tornado days composite charts of height, temperature, and humidity at 1000, 850, 700, 500, 300, 200, and 100 mb. not only for days on which tornadoes occurred in the Kansas and Nebraska area, but also for days on which tornadoes occurred in four other areas. The total of five areas covers the path of the annual march of the maximum of tornado frequency. Many other variables were tried, but with little or no forecasting success. Included among variables that were less effective as predictors than those discussed above were:

1. Measures of temperature advection at levels other than at 700 mb.
2. Various measures of stability and convective instability.
3. Measures of time-rate of change of convective

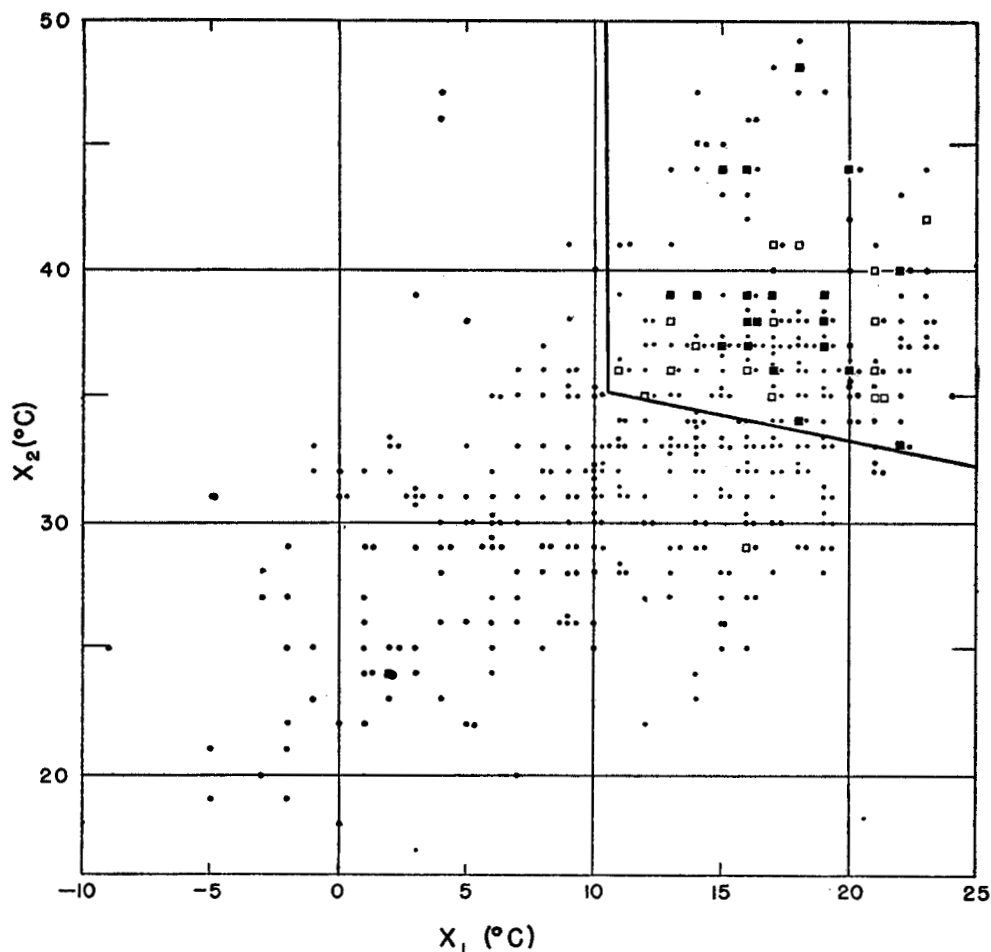


FIGURE 2.—The higher surface dew point ( $X_1$ ) at Columbia, Mo., or Dodge City, Kans., against the difference ( $X_2$ ) between the 500-mb. temperature at Grand Junction, Colo., and the surface temperature at either Columbia or Dodge City, whichever has the higher dew point. Temperatures and dew points are expressed in degrees Celsius (centigrade). All quantities were measured at 0900 CST for each day of the 14 months of April, May, and June, 1947 through 1950, and May and June, 1946. The dots are non-tornado days, the squares tornado days. Solid squares are major tornado days, open squares minor tornado days.

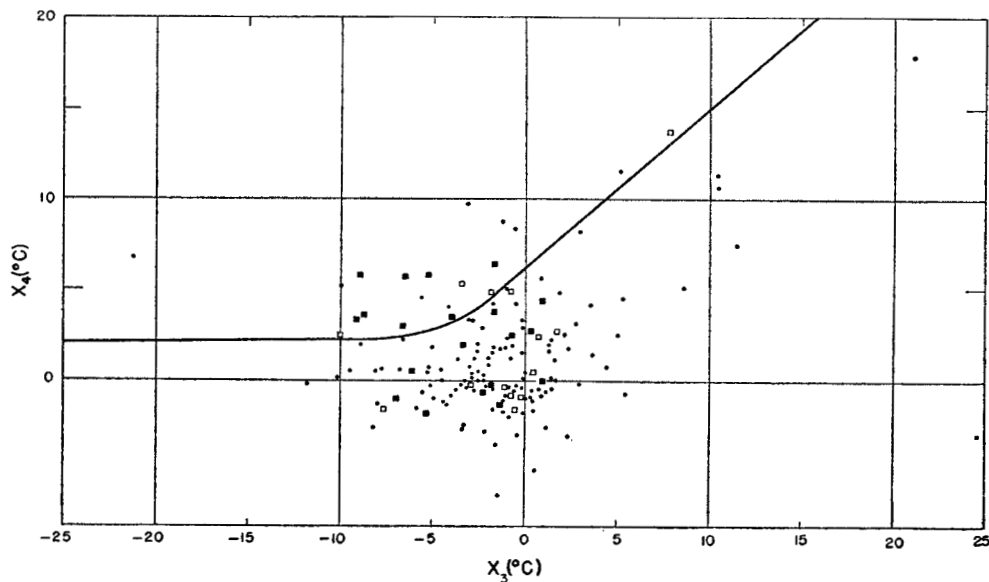


FIGURE 3.—Temperature advection ( $X_4$ ) over the triangle with vertexes at Dodge City, Kans., Oklahoma City, Okla., and Omaha, Nebr., against temperature advection ( $X_3$ ) over the triangle with vertexes at Albuquerque, N. Mex., Big Spring, Tex., and North Platte, Nebr. Temperature advection is expressed in degrees Celsius (centigrade) per 12 hours. A positive sign indicates cold air advection. All quantities were measured at 700 mb. at 0900 CST for each of the 166 days which fell in the ruled-off area in the upper right hand corner of figure 2. The dots are non-tornado days, the squares tornado days. Solid squares are major tornado days, open squares minor tornado days.

instability, as determined by advection of equivalent potential temperature at different levels.

4. Measures of wind velocity and direction at 500 mb. (the effect of the Fawbush-Miller-Starrett "jet" was expected to contribute here).
5. Measures of the "funnel" in the equivalent potential temperature isopleths which occur in cross-sections on tornado days. These cross-sections are parts of case studies the Weather Bureau is making of 1951 and 1952 tornado situations.

By removing seasonal trends and introducing a new variable, six non-tornado days were separated out of the 20 threat days in figure 3. Thus, for the remaining 14 days, the degree of certainty was increased to  $12/14 = .857$ . In this further step, however, the number of cases being worked with were so few that no great reliance can be placed on the improved separation. The charts showing this refinement are not included here.

In figures 4 through 10, severe local storms which were reported near the area and period are plotted for seven of the eight threat days on which tornadoes did not occur. On the eighth threat day, 26 April 1948, no severe local storms were reported in or near the forecast area and period. The "near miss" character of these non-tornado days should give the forecaster confidence in allowing the system to guide him.

Considering for the moment that the seven threat days of figures 4 through 10 may be called near misses, in that tornadoes or storms closely related to tornadoes occurred

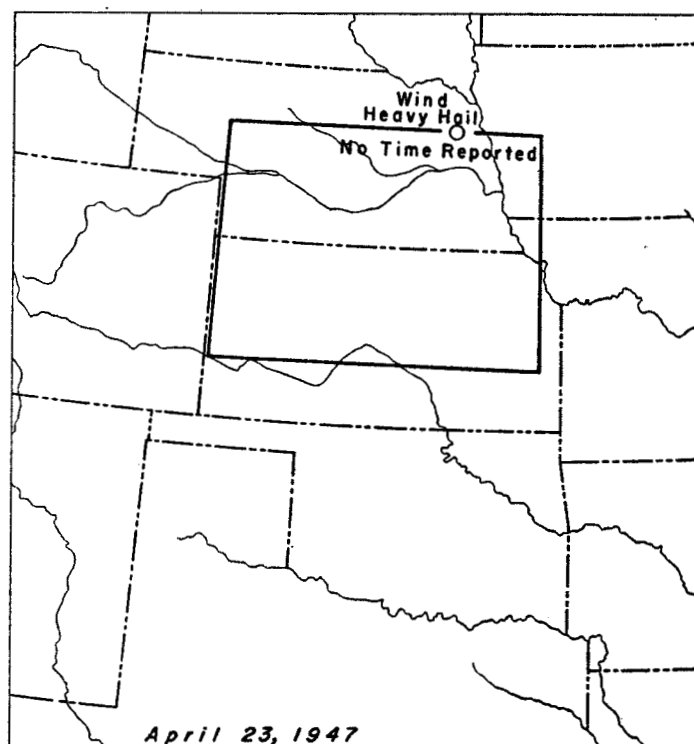


FIGURE 5.—Severe local storms which occurred on April 23, 1947, for which tornadoes were forecast but did not occur. The forecast area is blocked out, and the forecast period is 0900-2100 CST.

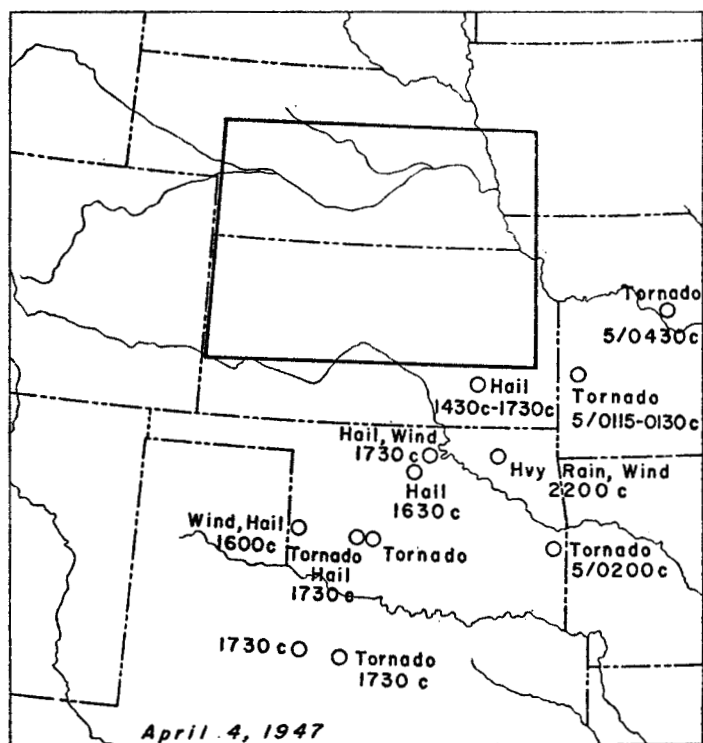


FIGURE 4.—Severe local storms which occurred on April 4, 1947, for which tornadoes were forecast but did not occur. The forecast area is blocked out, and the forecast period is 0900-2100 CST.

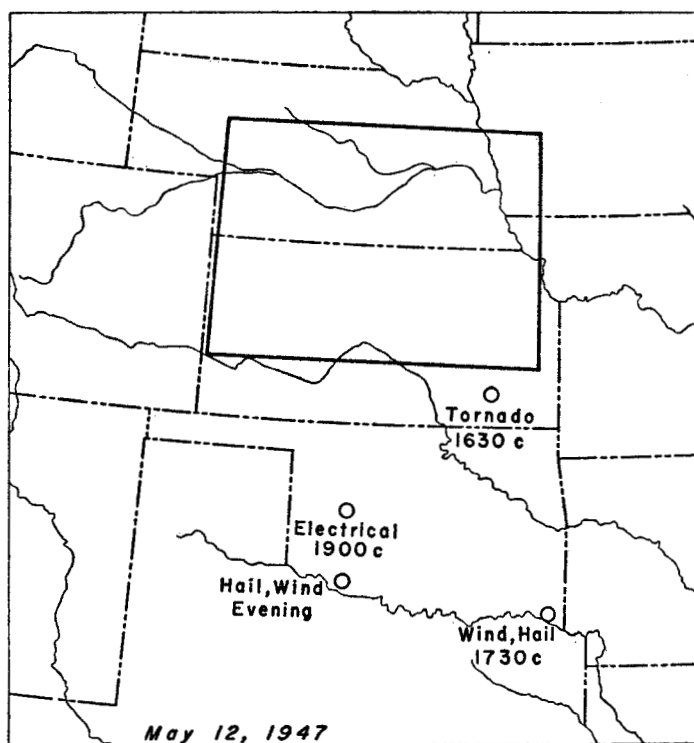


FIGURE 6.—Severe local storms which occurred on May 12, 1947, for which tornadoes were forecast but did not occur. The forecast area is blocked out, and the forecast period is 0900-2100 CST.

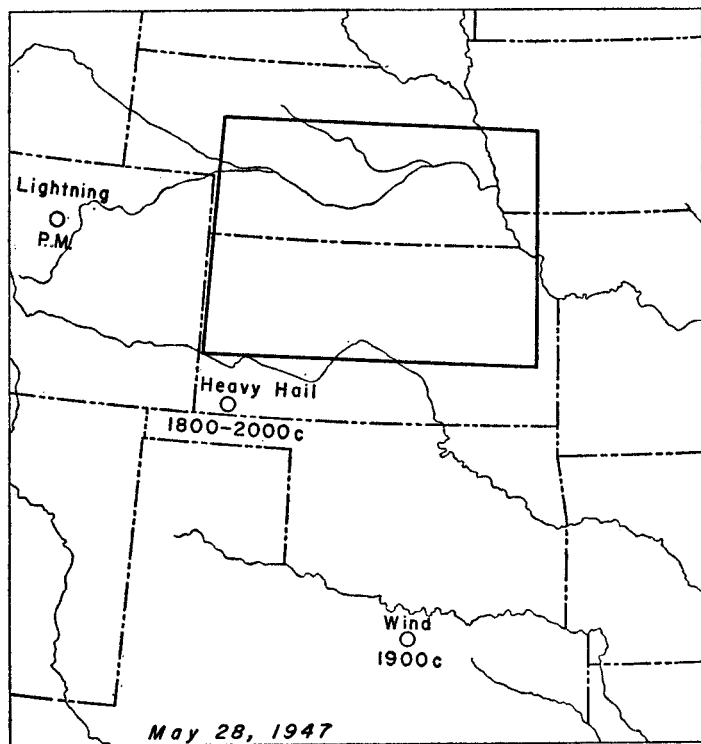


FIGURE 7.—Severe local storms which occurred on May 28, 1947, for which tornadoes were forecast but did not occur. The forecast area is blocked out, and the forecast period is 0900-2100 CST.

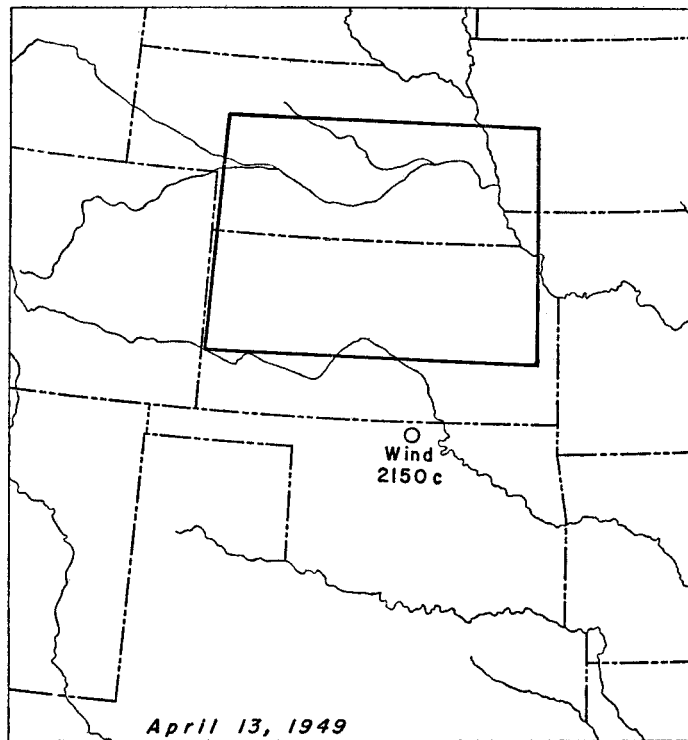


FIGURE 9.—Severe local storms which occurred on April 13, 1949, for which tornadoes were forecast but did not occur. The forecast area is blocked out, and the forecast period is 0900-2100 CST.

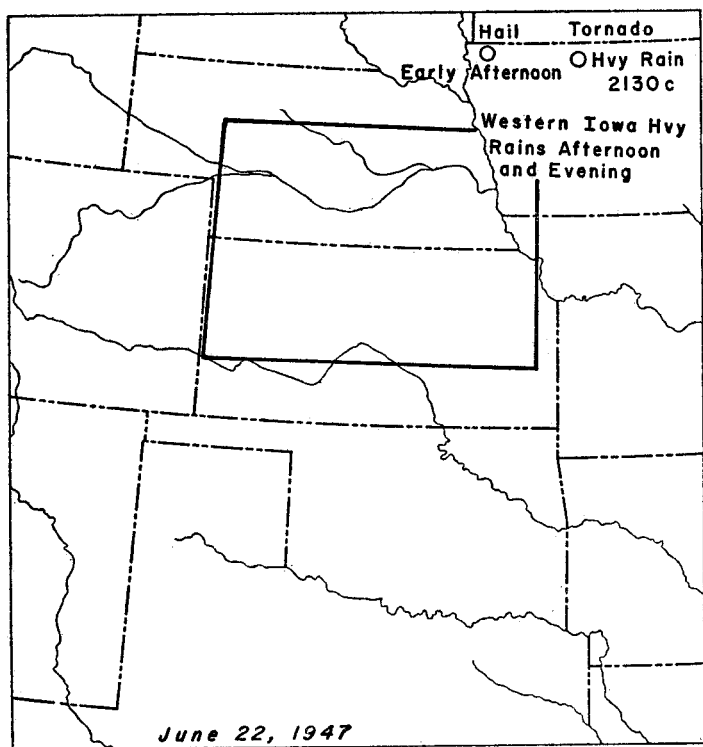


FIGURE 8.—Severe local storms which occurred on June 22, 1947, for which tornadoes were forecast but did not occur. The forecast area is blocked out, and the forecast period is 0900-2100 CST.

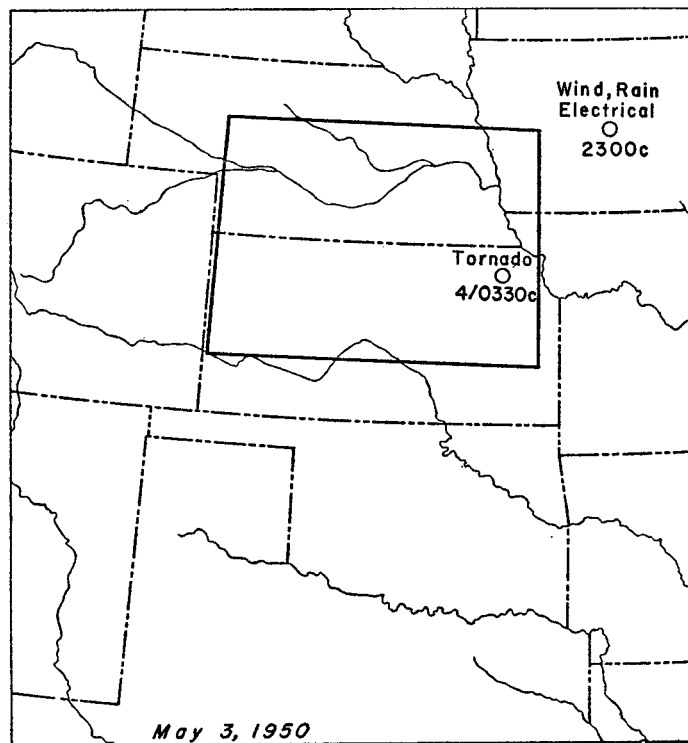


FIGURE 10.—Severe local storms which occurred on May 3, 1950, for which tornadoes were forecast but did not occur. The forecast area is blocked out, and the forecast period is 0900-2100 CST.

in or near the forecast area and during or soon after the forecast period, the probability of a "hit" or "near miss" for days falling under Group B is

$$P_B = 0.95.$$

It would be of interest to compare this figure with the corresponding figure for days falling under Group A, the non-threat days. A rough survey of severe local storm data for the 14 months shows that the probability of severe local storms occurring in or near the forecast area and during or soon after the forecast period on non-threat days is

$$P_A < 0.37.$$

The precise  $P_A$  corresponding to  $P_B = 0.95$ , is probably considerably less than 0.37, since the count of severe local storms was made within an area larger than the area of figures 4 through 10, and no great care was taken in distinguishing local severe storms from high winds and heavy rain of a general character, such as those associated with the large-scale cyclones. From the same count, it was determined that the climatological probability of severe storms in or near the forecast area and during or soon after the forecast period is

$$P_{cl} < 0.52.$$

#### CONCLUDING REMARKS

An important conclusion which may be drawn from this study is that objective forecasting techniques may be applied to the tornado problem with some degree of success. In this respect, tornado forecasting is no different from the forecasting of other weather elements. In summarizing this system as a forecasting tool, it must be remembered that it has not been tested on independent data. On dependent data it yielded, with a high degree of accuracy, forecasts of no tornadoes on about 60 percent of all spring days. It indicated in advance a group of days on which forecasts of tornadoes verified fairly well. The latter group of days included about one-third of all tornado days.

As an empirical study this investigation brings out clearly the dependence of tornado occurrence on both humidity and a deep air mass contrast across the area. It also suggests that one set of conditions which favor tornado occurrence, given the former two, is for the two air masses to be in pronounced motion around a 700-mb. trough. This is indicated by the temperature advection chart, figure 1. The failure of stability parameters mentioned previously indicates that stability measurements may not be as good a forecast tool as is now so widely believed. It is not reasonable to suppose that tornadoes occur in the presence of stability. It does not necessarily follow from this fact alone, however, that instability is consistently a useful forecast tool. For instability to be a consistently good forecast tool, it must be capable of being forecast consistently. From experience in forecasting tornadoes during the 1952 season, the authors have found that in some cases instability measurements largely

determine a forecast of tornadoes. If these cases are relatively few, an objective technique such as this study would not indicate them clearly. It must also be kept in mind in this connection that the failure of instability parameters may be due to the rigid manner in which they were put into the system. The flexibility of the usual forecasting methods may be better able to make use of instability measurements.

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#### APPENDIX

##### DEVELOPMENT OF FORMULAS FOR COMPUTING TEMPERATURE ADVECTION BY TRIANGULATION

List of symbols:

- $x, y$  Cartesian coordinates in a horizontal plane
- $u, v$   $x$  and  $y$  components of the velocity, respectively
- $z$  height of a constant pressure surface
- $g$  acceleration of gravity
- $f$  Coriolis parameter
- $\mathbf{V}$  horizontal wind velocity vector
- $\nabla$  horizontal gradient
- $A$  area of the triangle
- $T$  temperature

Consider the triangle of figure 11. Arbitrarily we let one vertex be at the origin, and one side coincide with the  $x$ -axis. It is assumed that within the triangle the temperature and height fields are linear, i.e. that they satisfy the following relations,

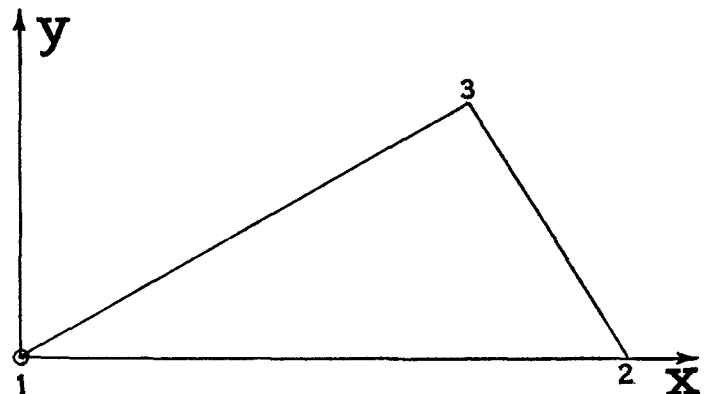


FIGURE 11.—Layout of a triangle used for computing temperature advection.

$$\begin{aligned} z &= a + bx + cy \\ T &= a' + b'x + c'y \end{aligned} \quad (1)$$

where  $a, b, c, a', b', c'$  are constants determined by the particular height and temperature fields at hand. It is further assumed that the wind is geostrophic, i.e.,

$$\begin{aligned} u &= -\frac{g}{f} \frac{\partial z}{\partial y} \\ v &= +\frac{g}{f} \frac{\partial z}{\partial x} \end{aligned} \quad (2)$$

The expression for temperature advection is

$$\mathbf{V} \cdot \nabla T = u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \quad (3)$$

where a positive value indicates cold air advection.

If substitutions are made from equations (2) into the quantity (3) we find that

$$\mathbf{V} \cdot \nabla T = \frac{g}{f} \left( -\frac{\partial T}{\partial x} \frac{\partial z}{\partial y} + \frac{\partial T}{\partial y} \frac{\partial z}{\partial x} \right) \quad (4)$$

The values for  $T$  and  $z$  in equations (1) may be substituted into equation (4). Then

$$\mathbf{V} \cdot \nabla T = \frac{g}{f} (-b'c + c'b) \quad (5)$$

The values of  $b, c, b', c'$  may be determined by evaluating equations (1) at the 3 vertexes of the triangle of figure 11. The subscripts in the following 2 sets of 3 simultaneous equations refer to values at the vertexes of figure 10.

$$\begin{aligned} z_1 &= a \\ z_2 &= a + bx_2 \\ z_3 &= a + bx_3 + cy_3 \\ T_1 &= a' \\ T_2 &= a' + b'x_2 \\ T_3 &= a' + b'x_3 + c'y_3 \end{aligned} \quad (6)$$

If equations (6) are solved simultaneously for  $b, c, b', c'$  and the results substituted into equation (5), then

$$\mathbf{V} \cdot \nabla T = \frac{g}{2Af} [(z_2 - z_1)(T_3 - T_1) - (z_3 - z_1)(T_2 - T_1)] \quad (7)$$

$$\mathbf{V} \cdot \nabla T = \frac{g}{2Af} [z_1(T_2 - T_3) + z_2(T_3 - T_1) + z_3(T_1 - T_2)] \quad (8)$$

Equation (7) is more adaptable to hand computation, while equation (8) is more adaptable to computation with a hand computing machine.